Optimal Management of Water, Nutrient and Carbon Cycles of Green Urban Spaces

H51G-1561 - Optimal Management of Water and Nutrient in Green Urban Spaces

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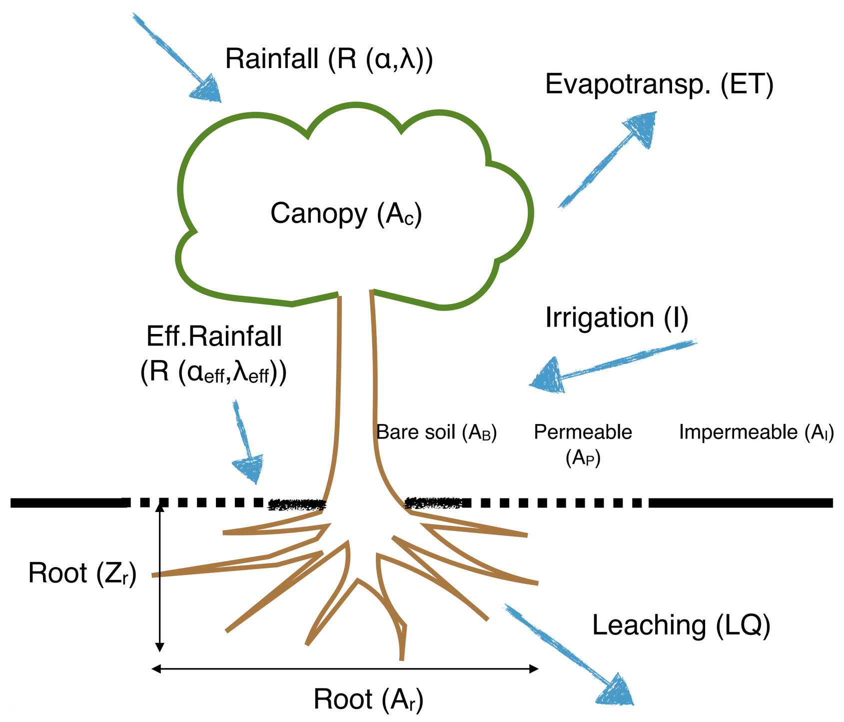
Motivations

- Green urban spaces are important parts of the urban environmental system.
- They provide several ecosystem services (e.g. positive effects on human health, social dynamics, housing prices and business district activity, reduced run-off, improved soil drainage, soil erosion control, watershed protection and provision of wildlife habitats and ecological corridors, urban heat island mitigation, cooling and reduction of energy demand in adjacent buildings and alleviation of air pollution and dust,…).
- We live in a changing urban environment (e.g. climate change, seasonality, heat islands, increasing urbanization, paved and impermeable surfaces,…)

and goals

- We need tools for the quantification of the provided ecosystem services (e.g. water and nutrient fluxes).
- We need tools for a sustainable and optimal management of green urban spaces (e.g. specie selection, water irrigation requirement, fertilization, urban design, water stress,…).



Platanus Acerifolia - Torino (Italy)

Ficus macrophylla - Palermo (Italy)

Quercus phellos - Durham (US)

Problem geometry and examined cases

- We concentrated on urban trees.
- The geometry is represented by canopy and root extensions.
- We consider different types of soil and geometries: bare soil, permeable pavements and impervious surfaces.
- The seasonality and climate characteristics are related to rainfall frequency, mean rainfall depth and transpiration temporal behaviors.
- We apply the model to different cities with contrasting climate conditions.
- We examine different irrigation schemes: micro-irrigation and traditional irrigation.

Mathematical Model

- We propose a minimalistic model that couples, at the daily temporal scale and at the tree spatial scale, the soil moisture (s) dynamic with a single pool nutrient (N) model.

$$nA_rZ_r\frac{ds(t)}{dt} = R(t) + I[s(t),t] - ET[s(t),t] - LQ[s(t),t]$$

$$\frac{dN(t)}{dt} = DEP + NIT - UP - LE - DEN$$

- Water input: stochastic rainfall R and irrigation I
- Water losses: evapotranspiration ET, leaching and runoff LQ
- Nutrient input: deposition DEP and nitrification NIT
- Nutrient losses: plant uptake UP, leaching LE and denitrification DEN

Rainfall stochasticity, geometry design

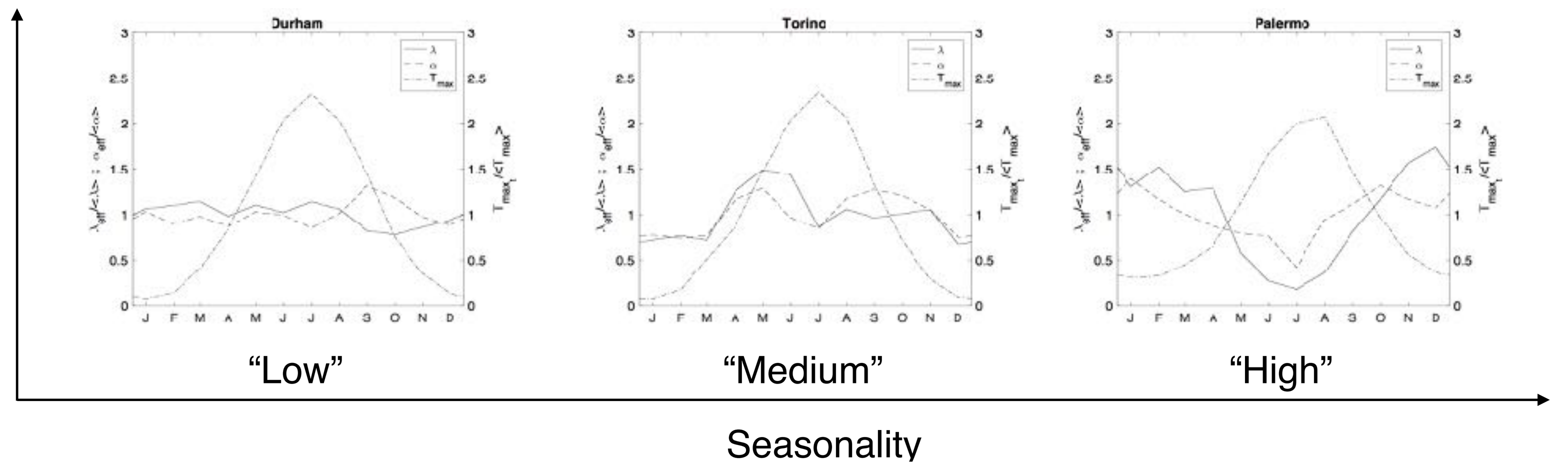
- The effective water volume that reaches the root zone is the link between the rainfall (stochastic process) and the geometry of the permeable and impermeable zones.
- if k_i and η_i are the fractions of soil area (B = bare, P = permeable, I = impermeable) influenced by the presence of canopy and the permeability, respectively, the effective rainfall mean depth α_{eff} and the effective rainfall frequency λ_{eff} are:

$$\alpha_{eff}(t) = \frac{\alpha(t)}{A_R}\left(\sum_i^{B,P,I}\eta_i A_i - (1-\kappa_C)\sum_i^{B,P,I}\eta_i k_i A_i\right)$$

$$\lambda_{eff}(t) = \lambda(t)\left[1-\left(1-e^{-\Delta/\alpha(t)}\right)\frac{\sum_i^{B,P,I}k_iA_i}{\sum_i^{B,P,I}A_i}\right]$$

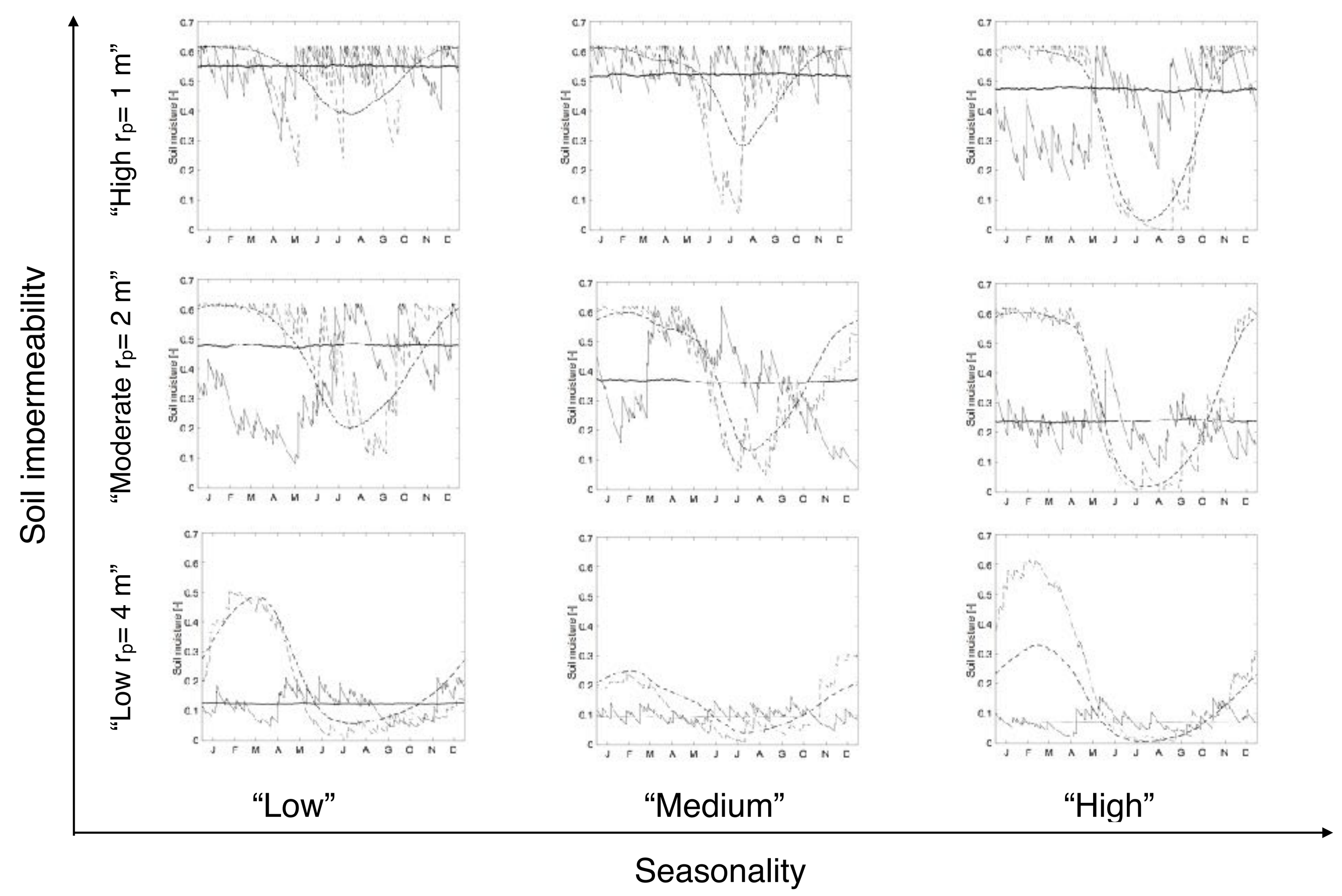
Seasonality

- The effective rainfall frequency and the rainfall mean depth, as well as transpiration, exhibit a seasonal pattern depending on the climatic and geographical position of the considered site.



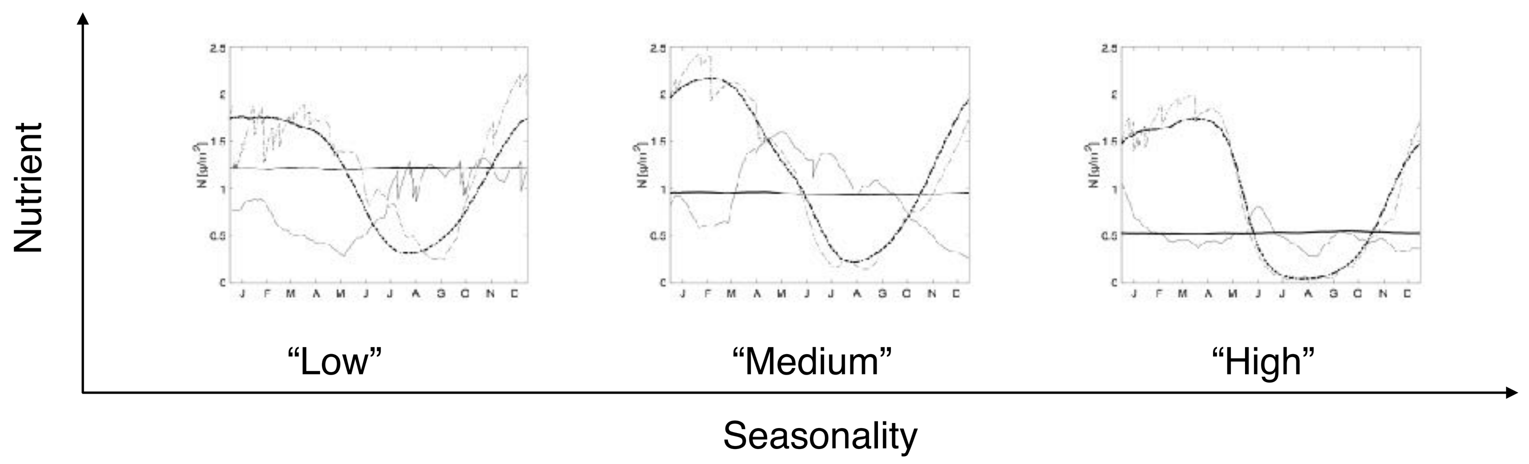
Soil moisture dynamic

- Soil moisture behavior: for an increasing seasonality and surface increasing impermeability the figure shows some examples of soil moisture time series with or without seasonality (thin continuous and thin dashed lines) and the corresponding annual mean behavior (bold lines)



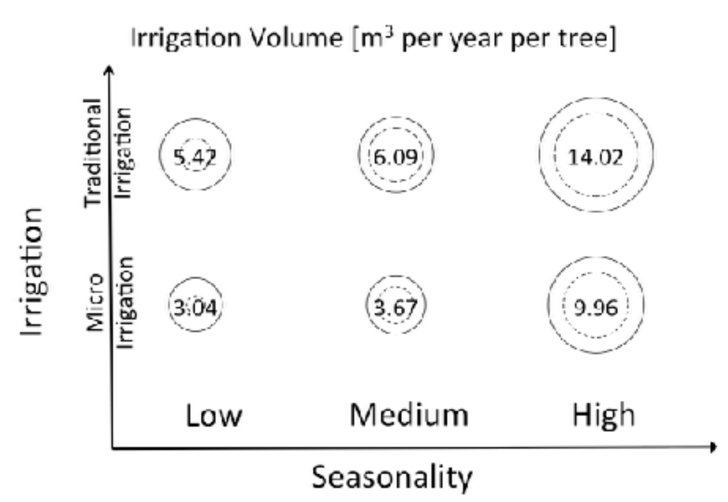
Nutrient dynamic

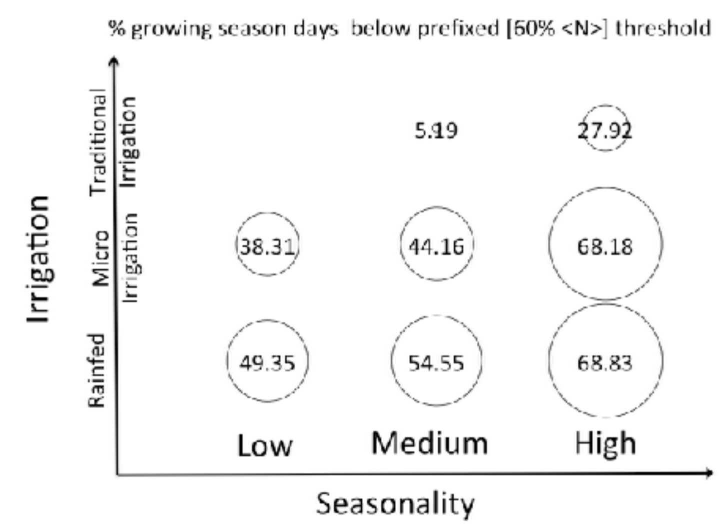
- Seasonality and permeability characteristics of the soil greatly impact on the nutrient behavior Here we present three samples of nutrient dynamic and the mean annual behaviors for a moderate permeable/impermeable ratio and with rainfed conditions (lines as in previous figure)



Indication for an optimal water and nutrient management

- Irrigation requirements as well as sustainability, cost and feasibility of the irrigation schemes depend on plant geometry, specie selection and rainfall pattern
- The "high" seasonality greatly impacts on irrigation water volume while "low" and "medium seasonalities present similar values.
- Seasonality impacts from 54% to 88% (with respect to climatic constant conditions) for the moderate permeable/impermeable ratio (dashed circle in figure). For low ratio the range is 83% ÷ 96%, while for high ratio is 1% ÷ 59%.
- We determine the number of days during the growing season in which the soil nitrogen is below a prefixed threshold (e.g. 60% of the mean soil nutrient content): as aspected the traditional scheme remarkably reduces the number of days below the threshold while the micro irrigation scheme shows lesser impact.
- The mean impacts of seasonality on mean annual soil nutrient contents are 75%, 25% and 53% for rained system, traditional irrigation and micro irrigation, respectively. The corresponding values for maxima and minima are 63%, 35%, 51%, and 97%, 29%, 58%.
- The max-min mean annual nutrient soil content ranges from 0.59 gN/m^2 to 1.72 gN/m^2.





Conclusions

- The model can be transformed in a useful tool for designers who have to evaluate the influence of the different materials (and related permeability) in urban landscape.
- The nutrient behavior can be related to optimal fertilization strategies, with a clear determination of fertilization amount, periods and costs.
- The forecasted climate changes can be taken in account through a variation of the parameters involved in the proposed model;

and future improvements

- Explore a wider range of parameters and climatic conditions.
- Explore the feasibility of fertilization strategies.
- Add the carbon cycle components
- Evaluate the economic value of the ecosystem services related to soil moisture and nutrients.

References

- Feng, X., Porporato, A., Rodriguez-Iturbe, I., 2014. Stochastic soil water balance under seasonal climates. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 471 (2174).
- Matthews T., Lo A.Y., Byrne J.A., 2015. Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. Landscape and Urban Planning 138, 155–163.
- Mullaney J., Lucke T. Trueman, S.J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landscape and Urban Planning 134, 157–166.
- Pataki D.E., Carreiro M.M., Cherrier J., Grulke N.E., Jennings V., Pincetl S., Pouyat R.V., Whitlow T.H., Zipperer W.C., 2011a. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Frontiers in Ecology and the Environment 9 (1), 27–36.
- Rodrıguez-Iturbe I., Porporato, A. 2007. Ecohydrology of Water-Controlled Ecosystems: Soil Moisture and Plant Dynamics. Cambridge University Press.
- Vico G., Revelli R., Porporato A., 2014. Ecohydrology of street trees: design and irrigation requirements for sustainable water use. Ecohydrology 7 (2), 508–523.

Acknowledgments

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